Economics of Climate Change

Reading for Microeconomics class (Long)

The material is sourced from the following undergraduate textbooks :

Chiang, E. (2019). Microeconomics: Principles for a Changing World (5th ed.). Worth Publishers. ISBN 978-1319218393.

The CORE Econ Team (2023) The Economy 2.0: Microeconomics Open access e-text https://core-econ.org/the-economy/.

Goodwin, N., Harris, J. M., Nelson, J. A., Rajkarnikar, P. J., Roach, B., & Torras, M. (2018). Microeconomics in Context (4th ed.). Routledge. ISBN 978-1-138-314566.

Tyler Cowen, Alex Tabarrok (2020). Modern Principles of Microeconomics (5th ed.). Macmillan Learning. ISBN: 9781319384029.

Hal R. Varian (2019). Intermediate Microeconomics: A Modern Approach (9th ed.). W.W. Norton & Co. ISBN: 978-0393689877.

Paul Krugman, Robin Wells (2018). Microeconomics (5th ed.). Worth Publishers. ISBN: 978-1-319-098780.

Robert S. Pindyck, Daniel L. Rubinfeld (2017). Microeconomics, Global Edition (9th ed.). Pearson. ISBN: 978-1-292-213316.

Austan Goolsbee, Steven Levitt, Chad Syverson (2019). Microeconomics (3rd ed.). Worth Publishers. ISBN: 978-1319105563.

No additional content has been added. We modified the layout to fit the format of this document, adding four titles for the main sections. We also removed irrelevant details, such as references to page numbers or figures that are not included in this document.

I – The Science of Climate Change

[Chiang, 2019, pp. 799-802]

Among the most significant economic issues facing the world today is the effect of human actions on the environment. There is scientific consensus that without a significant reduction in the production of greenhouse gases, which engulf the atmosphere and lead to global warming, irreversible damage to the climate, ecosystems, and coastlines will result. However, the course of action needed to address climate change deals with equity issues that are difficult on which to achieve consensus.

Understanding climate change?

Climate change refers to the gradual change in the Earth's climate due to an increase in average temperatures resulting from both natural and human actions. It is largely irreversible, particularly in its effect on rising sea levels and on ecosystems. According to the Intergovernmental Panel on Climate Change (IPCC), the average temperature "from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere."[1] And the trend has not ebbed, as average

[1] IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

temperatures in 2018 reached the highest ever recorded in modern times. Understanding the causes and effects of climate change is necessary to adopt appropriate actions to address the problem.

The causes of climate change

The primary causes of climate change are related to actions that emit greenhouse gases. Greenhouse gases created largely by human activities include carbon dioxide (CO_2) from fossil fuel and industrial processes, carbon dioxide (CO_2) from forestry and other land use (FOLU), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (F).

The largest portion of greenhouse gases is carbon dioxide, which is created by fossil fuel usage, industrial production, and deforestation. Fossil fuel usage includes the use of automobiles and airplanes, electricity and home heating fuels, and the production of products such as plastics and tires and even everyday items such as ink pens, cosmetics, and toothpaste. Deforestation contributes to greenhouse gases because trees absorb carbon dioxide, and when they are cut down or burned, the stored carbon dioxide is released into the atmosphere.

Other forms of greenhouse gases include methane, nitrous oxide, and fluorinated gases. Methane is generated largely from livestock farming, landfills, and the production and use of fossil fuels. Nitrous oxide is produced on farms from the use of synthetic fertilizers along with fossil fuel usage. Finally, fluorinated gases are created in products such as modern refrigerators, air conditioners, and aerosol cans. Because fluorinated gases do not harm the ozone layer and are energy efficient, products that emit these gases have grown in popularity over the past decade, though they still contribute significantly to global warming.

The consequences of Climate Change Today and in the Future

A sense of urgency surrounds climate change because the state of climate change science has advanced to the point where scientists are able to put probability estimates on certain impacts of warming, some of which are catastrophic. The major impacts of climate change are in the areas of food security, water resources, ecosystems, extreme weather events, and rising sea levels. The IPCC summarizes the consequences of climate change by listing five key "reasons for concern" as follows:

1. **Unique and threatened systems:** Many ecosystems are at risk, such as the diminishing Arctic sea ice and coral reefs, which leads to the extinction of species.
2. **Extreme weather events:** An increase in heat waves, heavy precipitation, and coastal flooding leads to major economic costs due to natural disasters and reductions in agricultural yields.
3. **Distribution of impacts:** The risks of climate change on disadvantaged people and communities are greater, especially those that depend on agricultural production.
4. **Global aggregate impacts:** Extensive biodiversity loss affects the global economy.
5. **Large-scale singular events:** Melting ice sheets will lead to rising sea levels, causing significant loss of coastal lands.

The difficulty with addressing these effects is that unlike air or water pollution that can be seen today, climate change has a cumulative effect. In other words, this year's CO_2 adds to that from the past to raise concentrations in the future. Once CO_2 levels reach a certain level, it may lead to extreme consequences that cannot be reversed. The global environment is essentially a common resource with many public goods aspects, and climate change is a huge global negative externality that extends long into the future.

[The CORE Econ Team, 2023, pp. 91-96]

New terms, new tools: Stocks and flows

To understand how the process of climate change could be contained, let's consider the underlying scientific process.

Burning fossil fuels for power generation and industrial use emits CO_2 into the atmosphere. Greenhouse gases such as CO_2 allow incoming sunlight to pass through the atmosphere, but trap reflected heat on the earth, leading to increases in atmospheric temperatures and changes in climate. Some CO_2 also gets absorbed into the oceans, increasing the acidity of the oceans and killing marine life.

The amount of CO_2 in the atmosphere is called the **stock**, while the amount being added per year is called the **flow.** To better understand what the terms stock and flow mean, consider Figure 2.19. The stock of CO_2 is the amount in the bathtub.

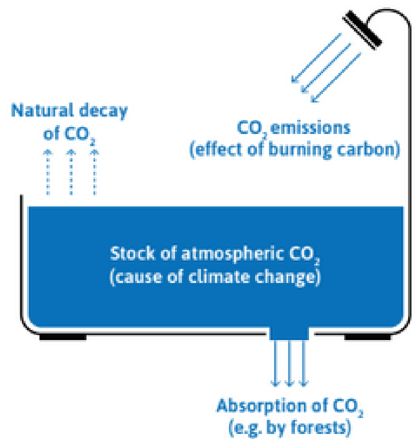

Figure 2.19 A bathtub model: the stock of atmospheric CO_2.

A flow is a measure based on a time period, like the number of tons of CO_2 per year. CO_2 emissions are an inflow that adds to the amount of atmospheric greenhouse gases, while the natural decay of CO_2 and its absorption (for example, by forests) are outflows that reduce the amount.

A key fact of climate science is that global warming results from the stock. It's what's in the tub that matters. The flow matters only because it will alter the stock. Figure 2.20 illustrates the movements in the stock of atmospheric CO_2 and annual temperatures.

The increase in the stock of atmospheric CO_2 is occurring because the outflows (natural decay, and absorption by forests and other carbon sinks) are far less than the new emissions that we add annually. Moreover, deforestation in the Amazon, Indonesia, and elsewhere is reducing the CO_2 outflows while also adding to CO_2 emissions. Forests are often replaced by agriculture, which produces further green house gas emissions—including methane from livestock, and nitrous oxide from fertilizer overuse.

The natural decay of CO_2 is extraordinarily slow. Of the carbon dioxide that humans have put in the atmosphere since the mass burning of coal that started in the Industrial Revolution, two-thirds will still be there a hundred years from now. More than a third will still be 'in the tub' a thousand years from now. The natural processes that stabilized greenhouse gases in pre-industrial times have been entirely over whelmed by human economic activity. And the imbalance is accelerating.

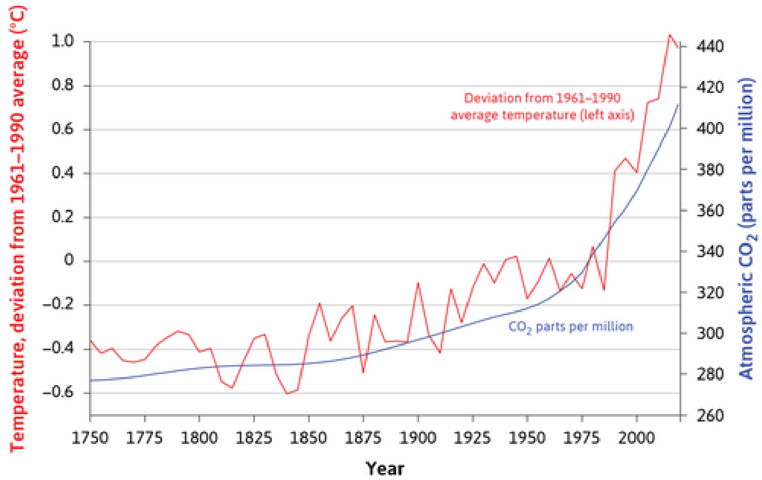

Figure 2.20 Global atmospheric concentration of carbon dioxide and global temperatures (1750 –2019).

A future without fossil fuels

The GDP hockey sticks in Figure 1.1, tell a powerful story of the entry of country after country onto the path of continuously rising average living standards—and of the many countries that have not yet experienced the transition to broad-based growth.

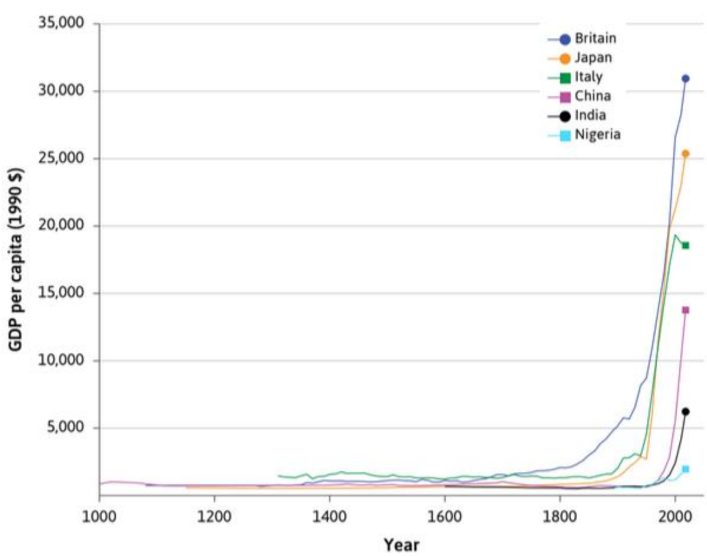

Figure 1.1 History's hockey stick: Gross domestic product per capita in five countries (1000–2018).

The production of energy is currently responsible for 87% of global greenhouse gas emissions. For the 85% of the global population who live below the level considered poor in a high-income country, is a fossil fuel-based transition to that standard of living in their future?

The evidence from climate science says that the growth in world production that would be required to raise incomes this much (estimated to be more than four times the size of today's total output) will have to be based on renewable energy combined with reduced energy input per unit of consumption.

How quickly this happens and at what cost depends critically on the policies that governments pursue; and these differ across countries. Figure 2.21 shows the link between rising living standards and CO_2 emissions: countries where GDP per capita is higher tend to have higher CO_2 emissions as well. This is to be expected because greater income per capita is the result of a higher level of production of goods and services per capita, involving greater use of fossil fuels. The upward-sloping 'line of best fit' shows the average emissions per capita for each level of GDP per capita. Low emissions by low-income countries signal energy poverty, not green energy or energy conservation.

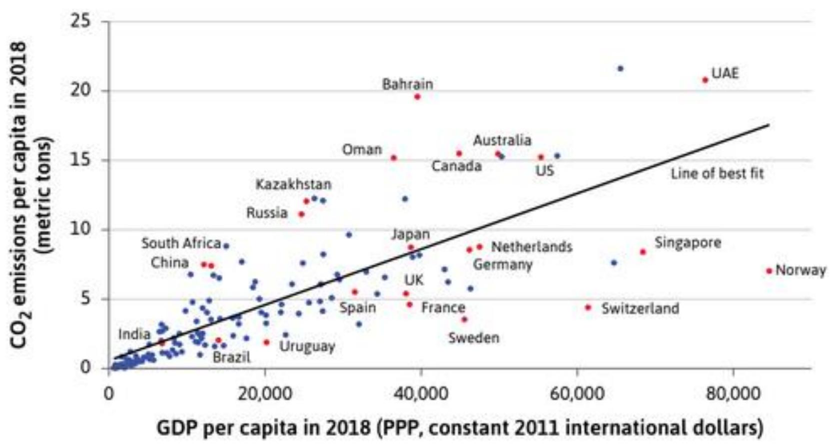

Figure 2.21 Carbon dioxide emissions are higher in richer countries.

But even among countries with similar per capita income, some emit much more than others. Compare the high emissions in the US, Canada, and Australia with the lower levels in France, Sweden, and Germany. Norway and Switzerland both have higher per capita incomes than the US but emit half as much CO_2.

This suggests that it is possible to organize production to offset, in part, the tendency for increased emissions as income rises. In low-emitting countries like France and Sweden, a substantial share of electricity is generated by non-fossil fuel sources (92% and 99% respectively) and petrol prices are much higher than in the countries with high emissions like the US and South Africa (above the line). For the poor countries on the left of the figure, their move to higher incomes needs to be a more nearly horizontal one rather than along the 'line of best fit'.

A transition to low-carbon electricity could occur simply by governments ordering it, but it would be more likely to happen—either by government order or by private decisions—if the energy from these sources is cheaper than from fossil fuels. Until well into the twenty-first century, electricity generated from renewables was far more expensive than from fossil fuels. Even in the absence of a carbon tax which will —as intended— raise the price of fossil fuel-based energy, prices have changed dramatically more recently. In most parts of the world, power from new renewable facilities is cheaper than from new fossil fuel ones.

The collapse in the price of renewable electricity generation since 1976 is illustrated vividly in Figure 2.22 by the data on the cost of photovoltaic cells for producing solar energy. This chart uses a different scale from other charts so far: it is a ratio (or equivalently, logarithmic) scale. Each step up the vertical axis corresponds to a doubling of the price, and each step along the horizontal axis multiplies the installed capacity by ten. The data points form close to a straight line: its slope tells us that a 10-fold increase in capacity roughly halves the cost.

Concentrating on the last ten years, Figure 2.23 compares the changes in the costs of generating electricity using renewables and fossil fuels. It is the relative price of electricity generation over the lifetime of the power plant that affects decisions to switch to a new technology: the changes in ranking

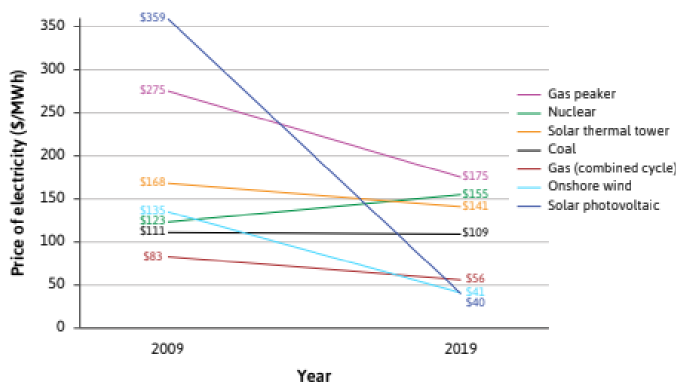

Figure 2.23 The price of renewable and non-renewable energy sources in 2009 and 2019.

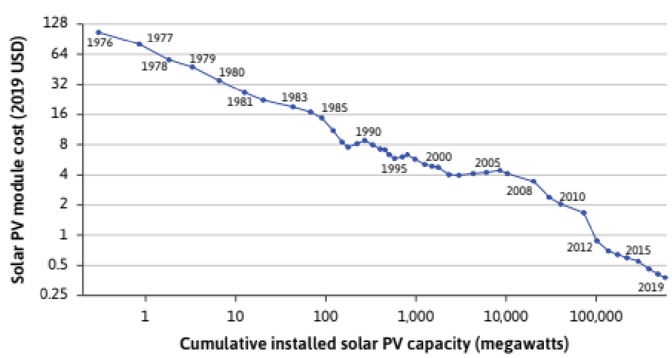

Figure 2.22 The price of photovoltaic cells (1976–2019).

of wind, and especially solar (from the most expensive to the least) mean that by 2019, 72% of all new additions to capacity worldwide have been in renewables.

It was government policies that initiated the exponential technological improvement in solar energy illustrated in Figure 2.22 above. Similarly rapid innovation characterized wind energy and lithium-ion batteries. The combined effect of government interventions and competitive markets drove progress. For example, subsidies for solar energy began in the 1970s in several countries including Japan, Germany, the US, and China. The schemes created incentives for energy providers to use solar and private companies to compete for market share. Equally important was government research funding (mainly in the US) leading to scientific advances that were applied to develop new solar cell materials and panel designs more efficient at converting sunlight to electricity.

The technological progress in renewables is a sign that a path to higher living standards without fossil fuels may be possible. But whether this is feasible on the scale required both to arrest climate change and make a serious dent in global poverty is doubtful.

[Goodwin et al., 2018, p. 425]

Climate change: long-term changes in global climate, including warmer temperatures, changing precipitation patterns, more extreme weather events, and rising sea levels.

The scientific consensus on climate change is well-established-approximately 97 percent of scientists studying the issue conclude that human emissions of various greenhouse gases, primarily carbon dioxide (CO_2), are significantly impacting the global climate system.[2] According to the National Aeronautics and Space Administration (NASA), 2014, 2015, and 2016 each set a new record for the warmest year on record, and 16 of the 17 warmest years have occurred since 2001.[3]

Climate change has significant economic costs. According to the OECD, the economic damages from climate change are estimated to be between 1.0 percent and 3.3 percent of world economic output by 2060, rising to between 2 percent and 10 percent of global output by 2100.[4] Other research suggests the damages will be even larger-around 10 percent of global output by as soon as 2050 according to the United Nations."[5] But the negative consequences of climate change are already occurring. According to a 2017 report, the damages from climate change are already currently averaging $240 billion per year in the United States, effectively offsetting about 40 percent of the economic growth in the United States.[6] Another study estimated that 400,000 deaths in 2010 were attributable to climate change, primarily as a result of malnutrition and disease, with over 80 percent of those deaths in developing countries.[7]

Policy responses to limit the future damages from climate change need not sacrifice economic vitality. In 2013 the managing director of the International Monetary Fund, Christine Lagarde, called climate change "the greatest economic challenge of the twenty-first century." She went on to say:

Make no mistake: without concerted action, the very future of our planet is in peril. So we need growth, but we also need green growth that respects environmental sustainability. Good ecology is good economics.[8]

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[2] Cook, John, Dana Nuccitelli, Sarah A. Green, Mark Richardson, Bärbel Winkler, Rob Painting, Robert Way, Peter Jacobs, and Andrew Skuce. 2013. "Quantifying the Consensus on Anthropogenic Global Warming in the Scientific Literature." Environmental Research Letters, 8(2): 024024.

[3] National Aeronautics and Space Agency (NASA). 2017. "NASA, NOAA Data Show 2016 Warmest Year on Record Globally." NASA Press Release, January 18, 2017. https://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally.

[4] OECD. 2015. The Economic Consequences of Climate Change. OECD Publishing, Paris.

[5] Climate Vulnerable Forum (CVP) and United Nations Development Programme (UNDP). 2016. "Pursuing the 1.5°C Limit: Benefits and Opportunities."

[6] Watson, Robert, James J. McCarthy, and Liliana Hisas. 2017. "The Economic Case for Climate Action in the United States." Universal Ecological Fund (FEU-US), September 2017.

[7] DARA and Climate Vulnerability Forum (CVF). 2012. "Climate Vulnerability Monitor, 2nd Edition." Madrid, Spain.

[8] Hance, Jeremy. 2013. "Head of IMF: Climate Change Is 'the Greatest Economic Challenge of the 21st Century'." Mongabay, Februa ry6, 2013.

[The CORE Econ Team, 2023, pp. 6-8]

After having remained relatively unchanged for many centuries, increasing emissions of carbon dioxide (CO_2) into the air during the twentieth and twenty-first centuries have resulted in measurably larger amounts of CO_2 in the earth's atmosphere (Figure 1.2a) and brought about perceptible increases in the northern hemisphere's average temperatures (Figure 1.2b). Figure 1.2a also shows that CO_2 emissions from fossil fuel consumption have risen dramatically since the late 1800s. Figure 1.2b shows that the mean temperature of the earth fluctuates from decade to decade. Many factors cause these fluctuations, including volcanic events such as the 1815 Mount Tambora eruption in Indonesia.

Since 1900, average temperatures have risen in response to increasingly high levels of greenhouse gas concentrations. These have mostly resulted from the CO_2 emissions associated with the burning of fossil fuels. And in each year of the twenty-first century, the average temperature has been higher than at any time in the previous millennium. The human causes and the reality of climate change are no longer widely disputed in the scientific community. The likely consequences of global warming are far- reaching: melting of the polar ice caps, rising sea levels that may put large coastal areas under water, and potential changes in climate and rain patterns that may make some densely populated parts of the world uninhabitable and destroy the world's food-growing areas.

We can see that the hockey sticks for GDP per capita and for atmospheric CO_2 have risen together. It is also the case that richer countries have, on average, higher emissions per capita.

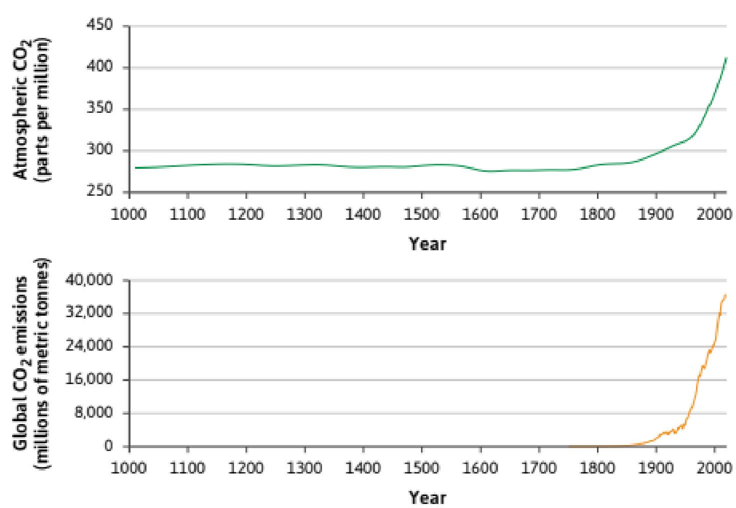


Figure 1.2a Carbon dioxide in the atmosphere (1010–2020) and global carbon emissions from burning fossil fuels (1750–2018).

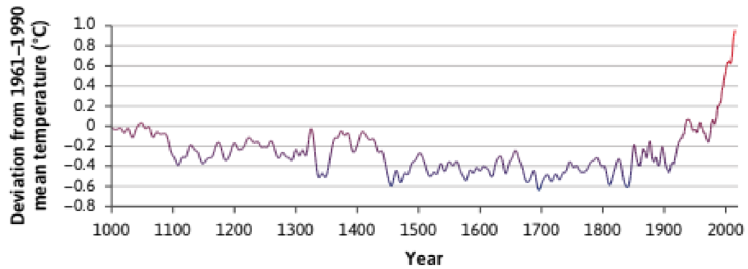


Figure 1.2b Northern hemisphere temperatures over the long run (1000–2019). The figure shows 5-year moving averages.

[Goodwin et al., 2018, p. 427]

As atmospheric concentrations of greenhouse gases increase, the world is expected to become warmer, on average. Not all regions will warm equally, and some regions may actually become cooler. Warmer average temperatures increase evaporation, which in turn leads to more frequent precipitation, but again all regions will not be affected equally. In general, areas that are already wet will become wetter and dry areas will become drier. Climate change is also expected to result in more frequent and more intense tropical storms. The melting of polar ice caps and glaciers will contribute to rising sea levels. Sea levels are also rising because the volume of ocean water expands when it is heated.

Global average temperatures have already increased by about 1 degree Celsius (1.8 degrees Fahrenheit) over the past several decades. At the 2015 international climate meeting in Paris, nearly 200 nations agreed that it was necessary to limit the eventual warming to "well below" 2 degrees Celsius, and to "pursue efforts" to limit the warming to 1.5 degrees Celsius, based on the scientific consensus that warming above these levels is likely to cause dangerous economic and ecological impacts.[9]

Climate scientists have developed complex models to predict how much average temperatures will increase as CO_2, concentrations increase. Because predicting long-term climate trends involves considerable uncertainty, these models have produced a range of potential outcomes. Adding to the uncertainty in models is the extent to which warming will be influenced by the policy decisions made in the next couple of decades.

The Intergovernmental Panel on Climate Change (IPCC) was established in 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) to assess the science of climate change. A 2014 IPCC report concludes that human emissions of greenhouse gases "are extremely likely to have been the dominant cause of the observed warming since the mid-20th century" and that "continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system."[10] The report estimates that the global temperature increase by 2100, relative to the pre-industrial average temperature, will be from 1.0 degree Celsius (1.8 degrees Fahrenheit) to as high as 5.4 degrees Celsius (9.7 degrees

[9] http://unfccc.int/paris_agreement/items/9485.php.

[10] Intergovernmental Panel on Climate Change (IPCC). "Climate Change 2014: Synthesis Report, Summary for Policymakers." Geneva, Switzerland.

Fahrenheit), reflecting uncertainty in both physical modeling and policy actions. The negative impacts of climate change will fall disproportionately on developing countries. Warming above 4 degrees Celsius is considered particularly dangerous to poorer nations, with the IPCC estimating that this would result in a high risk of reduction in fresh water availability and food supplies, along with a spread in diseases and an increase in heat-related mortality.

[Goodwin et al., 2018, p. 428]

The economic debate over climate change changed significantly in 2006 when Nicholas Stern, a former chief economist at the World Bank, released a 700-page report, sponsored by the British government, titled "The Stern Review on the Economics of Climate Change." Publication of the Stern Review generated significant media attention and has intensified the debate over climate change in policy and academic circles. Unlike previous studies, the Stern Review strongly recommends immediate and substantial policy action:

The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response. This Review has assessed a wide range of evidence on the impacts of climate change and on the economic costs, and has used a number of different techniques to assess costs and risks. From all these perspectives, the evidence gathered by the Review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.

The Stern Review estimated that if humanity continues "business as usual," the costs of climate change in the twenty-first century would reach at least 5 percent of global GDP and could be as high as 20 percent. It also suggested the need for a much higher carbon tax-over $300 per ton of carbon.

What accounts for the difference between the Stern Review and most earlier analyses? The primary difference was that Stern applied a lower discount rate, 1.4 percent, compared to 3-5 percent in most other studies. Stern argued that his discount rate reflected the view that each generation should have approximately the same inherent value. Stern's analysis also incorporated the precautionary principle, in that he placed greater weight on the possibility of catastrophic damages.

[Cowen & Tabarrok, 2020, p. 206]

There are three types of government solutions to externality problems: taxes and subsidies, command and control, and tradeable allowances. Market prices do not correctly signal true costs and benefits when there are significant external costs or benefits. Taxes and subsidies can adjust prices so that they do send the correct signals. When external costs are significant, the market price is too low, so an optimal tax raises the price. When external benefits are significant, the market price is too high, so an optimal subsidy lowers the price.

Command and control solutions can work but are often high-cost because they are inflexible and do not take advantage of differences in the costs and benefits of eliminating and producing the externality.

II- Carbon pricing

[Chiang, 2019, p. 802]

Cleaning up pollution problems typically involves finding a level of abatement at which the marginal costs of abatement equal the marginal benefits. This can be achieved by taxing, assigning marketable permits, or using command and control policies to limit emissions.

[Varian, 2019, pp. 451-454]

Carbon Tax Versus Cap and Trade

Motivated by concerns about global warming, several climatologists have urged governments to institute policies to reduce carbon emissions. Two of these reduction policies are particularly interesting from an economic point of view: **carbon taxes** and **cap and trade.**

A carbon tax imposes a tax on carbon emissions, while a cap and trade system grants licenses to emit carbon that can be traded on an organized market. To see how these systems compare, let us examine a simple model.

Optimal Production of Emissions

We begin by examining the problem of producing a target amount of emissions in the least costly way. Suppose that there are two firms that have current levels of carbon emissions denoted by $(\bar{x}_1, \bar{x}_2)$. Firm i can reduce its level of emissions by x_i at a cost of $c_i(x_i)$. Figure 24.10 shows a possible shape for this cost function.

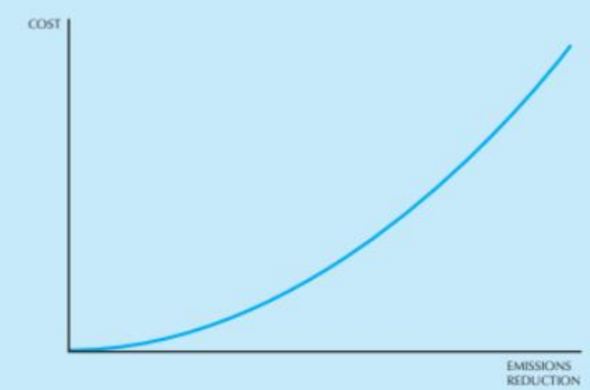


Figure 24.10 **Cost function for emissions.** The curve shows the cost associated with emission reductions.

The goal is to reduce emissions by some target amount, T, in the least costly way. This minimization problem can be written as

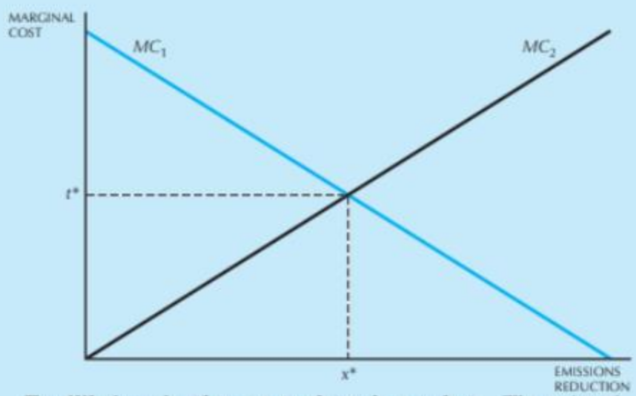
$$\min_{x_1, x_2} c_1(x_1) + c_2(x_2)$$

$$\text{such that } x_1 + x_2 = T.$$

If it knew the cost functions, the government could, in principle, solve this optimization problem and assign a specific amount of emission reductions to each firm. However, this is impractical if there are thousands of carbon emitters. The challenge is to find a decentralized, market-based way of achieving the optimal solution.

Let us examine the structure of the optimization problem. It is clear that at the optimal solution the marginal cost of reducing emissions must be the same for each firm. Otherwise it would pay to increase emissions in the firm with the lower marginal cost and decrease emissions in the firm with the higher marginal cost. This would keep the total output at the target level while reducing costs.

Hence we have a simple principle: at the optimal solution, the marginal cost of emissions reduction should be the same for every firm. In the two-firm case we are examining, we can find this optimal point using a simple diagram. Let $MC_1(x_1)$ be the marginal cost of reducing emissions by x_1 for firm 1 and write the marginal cost of emission-reduction for firm 2 as a function of firm 1's output: $MC_2(T - x_1)$, assuming the target is met. We plot these two curves in Figure 24.11. The point where they intersect determines the optimal division of emission reductions between the two firms given that T emission reductions are to be produced in total.



Equilibrium in the cap and trade market. The point t^* gives the optimal carbon tax and emissions license price. **Figure 24.11**

A Carbon Tax

Instead of solving for the cost-minimizing solution directly, let us instead consider a decentralized solution using a carbon tax. In this framework, the government sets a tax rate t that it charges for carbon emissions. If firm 1 starts with $\bar{x}_1$ and reduces its emissions by x_1, then it ends up with $\bar{x}_1 - x_1$ emissions. If it pays t per unit emitted, its carbon tax bill would be $t(\bar{x}_1 - x_1)$.

Faced with this tax, firm 1 would want to choose that level of emission reductions that minimized its total cost of operation: the cost of reducing emissions plus the cost of paying the carbon tax on the emissions that remain. This leads to the cost minimization problem

$$\min_{x_1} c_1(x_1) + t(\bar{x}_1 - x_1)$$

Clearly the firm will want to reduce emissions up to the point where the marginal cost of further reductions just equals the carbon tax, i.e., where $t = MC_1(x_1)$.

If the carbon tax is set to be the rate t^*, as determined in Figure 24.11, then the total amount of carbon emissions will be the targeted amount, T. Thus the carbon tax gives a decentralized way to achieve the optimal outcome.

[Krugman & Wells, 2018, p. 1036]

The term emissions tax may convey the misleading impression that taxes are a solution to only one kind of external cost, pollution. In fact, taxes can be used to discourage any activity that generates negative externalities, such as driving (which inflicts environmental damage greater than the cost of producing gasoline) or smoking (which inflicts health costs on society far greater than the cost of making a cigarette). In general, taxes designed to reduce external costs are known as Pigouvian taxes, after the economist A. C. Pigou, who emphasized their usefulness in his classic 1920 book, The Economics of Welfare.

[Varian, 2019, p. 454]

Cap and Trade

Suppose, alternatively that there is no carbon tax, but that the government issues tradable emissions licenses. Each license allows the firm that holds it to produce a certain amount of carbon emissions. The government chooses the number of **emissions licenses** to achieve the target reduction.

We imagine a market in these licenses so each firm can buy a license to emit x units of carbon at a price of p per unit. The cost to firm 1 of reducing its emissions by x1 is $c_1(x_1) + p(\bar{x}_1 - x_1)$. Clearly the firm will want to operate where the price of an emissions license equals the marginal cost, $p = MC_1(x_1)$. That is, it will choose the level of emissions at the point where the cost of reducing carbon emissions by one unit would just equal the cost saved by not having to purchase a license.

Hence the marginal cost curve gives us the supply of emissions as a function of the price. The equilibrium price is the price where the total supply of emissions equals the target amount T. The associated price is the same as the optimal carbon tax rate t^*in Figure 24.11.

The question that remains is how to distribute the licenses. One way would be to have the government sell the licenses to firms. This is essentially the same as the carbon tax system. The government could pick a price and sell however many licenses are demanded at that price. Alternatively, it could pick a target level of emissions and auction off permits, letting the firms themselves determine a price. This is one type of "cap and trade" system. Both of these policies should lead to essentially the same market-clearing price.

Another possibility would be for the government to hand out the licenses to the firms according to some formula. This formula could be based on a variety of criteria, but presumably an important reason to award these valuable permits would be building political support for the program. Permits might be handed out based on objective criteria, such as which firms have the most employees, or they might be handed out based on which firms have donated the most to some political causes. From the economic point of view, it doesn't matter whether the government owns the licenses and sells them to the firms (which is basically a carbon tax system) or whether the firms are given the licenses and sell them to each other (which is basically cap and trade).

[Goodwin et al., 2018, pp. 428-429]

Because climate change can be considered a very large environmental externality associated with carbon emissions, economic theory suggests a carbon tax as an economic policy response. Alternatively, a tradable permit system (also known as cap-and-trade) could be applied to carbon emissions.

Both approaches have been used. Carbon taxes have been instituted in several countries, including a nationwide tax on coal in India (about $1/ton, enacted in 2010), a tax on new vehicles based on their carbon emissions in South Africa (initiated in 2015), a carbon tax on fuels in Costa Rica (enacted in 1997), and local carbon taxes in the Canadian provinces of Quebec, British Columbia, and Alberta that apply to large carbon emitters and motor fuels.[11]

The European Union instituted a cap-and-trade system for carbon emissions in 2005. The system covers more than 11,000 facilities that collectively are responsible for nearly half the EU's carbon emissions. In 2012 the system was expanded to cover the aviation sector, including incoming flights from outside the EU. The goal of the EU program is to reduce greenhouse gas emissions by at least 40 percent, relative to 1990 levels, by 2040.[12] The state of California instituted a cap-and-trade system in 2013 for electrical utilities and large industrial facilities, with a goal of reducing greenhouse gas emissions in 2050 by 80 percent, relative to 1990 levels.[13]

According to most scientists, however, an adequate policy response to climate change will require actions at the international level. Each individual country has very little incentive for reducing its emissions if other countries do not agree to similar reductions. Action to reduce climate change can be regarded as a public good that also generates a positive externality. As we have noted, in the case of public goods, the problem of free riders means that they will not be provided effectively without collective action.

The 2015 Paris climate agreement provides the framework for an international response to climate change. As mentioned above, the goal of the agreement is to limit eventual warming to below 2 degrees Celsius, or even better to below 1.5 degrees Celsius. Rather than imposing universal climate policy mechanisms, such as a global carbon tax, or legally binding emissions targets, the Paris agreement is built upon voluntary "nationally determined contributions" (NDCs). Each participating country is free to set its own emissions targets, with some targets being relatively ambitious while others are comparatively modest. For example, Costa Rica has set strong interim targets along a path to become fully carbon neutral (no net carbon emissions) by 2085.[14] Other countries' NDCs have been rated "critically insufficient" by the nonprofit organization Climate Action Tracker, including Russia, Chile, and Saudi Arabia.

[Cowen & Tabarrok, 2020, pp. 202-206]

In January 2019, thousands of economists, including 27 Nobel laureates signed an open letter arguing that the best way to address the problem of climate change was a carbon tax. To quote the letter:

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[11] https://en.wikipedia.org/wiki/Carbon_tax.

[12] European Commission. 2016. "The EU Emissions Trading System (EU ETS)."https://ec.europa.eu/clima/sites/clima/files/factsheet_ets_en.pdf.

[13] https://www.arb.ca.gov/cc/capandtrade/capandtrade.htm.

[14] http://climateactiontracker.org/countries/costarica.html.

1. A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary. By correcting a well-known market failure, a carbon tax will send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors toward a low-carbon future.
2. A carbon tax should increase every year until emissions reductions goals are met and be revenue neutral to avoid debates over the size of government. A consistently rising carbon price will encourage technological innovation and large-scale infrastructure development. It will also accelerate the diffusion of carbon-efficient goods and services.
3. A sufficiently robust and gradually rising carbon tax will replace the need for various carbon regulations that are less efficient. Substituting a price signal for cumbersome regulations will promote economic growth and provide the regulatory certainty that companies need for long-term investment in clean-energy alternatives.
4. To prevent carbon leakage and to protect U.S. competitiveness, a border carbon adjustment system should be established. This system would enhance the competitiveness of American firms that are more energy-efficient than their global competitors. It would also create an incentive for other nations to adopt similar carbon pricing.
5. To maximize the fairness and political viability of a rising carbon tax, all the revenue should be returned directly to U.S. citizens through equal lump-sum rebates. The majority of American families, including the most vulnerable, will benefit financially by receiving more in "carbon dividends" than they pay in increased energy prices.

We can now understand each of these points. Point 1 reminds us that carbon released into the atmosphere contributes to climate change and thus imposes an eventual cost on bystanders. But note that the economists argue that the goal of a carbon tax is not to eliminate all carbon emissions, but to solve the market failure by correctly pricing carbon emissions. Remember, a price is a signal wrapped up in an incentive. Thus, by correctly pricing carbon emissions the market will send a signal about the true cost of different products and services and that signal will incentivize demanders and suppliers to reduce high-carbon products and develop substitutes. In other words, when carbon emissions are correctly priced, self-interest will align with the social interest so the invisible hand can steer economic actors in the right direction.

Point 1 also tells us that a carbon tax offers the most "cost-effective" lever to reduce carbon emissions. Point 2 explains some of the reasons why. A carbon tax operates on *many margins.* A carbon tax will encourage demanders to switch from higher-priced carbon-intensive goods and services to lower-priced, less-carbon intensive substitutes. At the same time, suppliers will be encouraged to research and develop less carbon-intensive goods and services. Over time a carbon tax will even encourage large-scale changes in how energy is generated, where people work and live and how they transport as well as produce goods and services.

Point 3 says that a carbon tax is better than command and control regulations. Remember the clothes washers that didn't work after command and control regulations on energy efficiency were imposed before the available technology was cost-effective? The same principles apply to a carbon tax. Instead of requiring that every new home install solar panels, a potentially very costly mandate imposed in California, the economists are suggesting that we apply a carbon tax and let people decide how to reduce carbon emissions in the least costly way. Command and control works on only a few margins, whereas a carbon tax works across many margins in ways that are too complex for planners to predict or plan. [...] A carbon tax uses the forces of creative destruction, which brought us cell phones, online dating, and movies on demand, to address the challenge of climate change.

Point 4 makes an important point that we have not made before. The problem of climate change is especially difficult to solve because the external cost of carbon emissions crosses all borders and boundaries. A carbon tax is unlikely to be effective if it is imposed by the United States alone. Indeed, it could be even counterproductive if relatively low-carbon U.S. producers were taxed but not higher-carbon foreign competitors. Thus, Point 4 suggests a border adjustment scheme so that at least within the United States all producers, foreign and domestic, would be taxed on a level playing field. The United States is one of the world's largest markets, so Point 4 suggests that this will encourage other countries to adopt carbon taxes. Getting both the economics and the politics right is one of the most difficult parts of designing a global carbon tax.

The politics of a carbon tax are also discussed in Points 2 and 5. Point 2 argues that a carbon tax should be "revenue neutral." The signatories to the letter don't necessarily agree on whether the government should spend more or less money on defense or Medicare or the National Institutes of Health. What they do agree on is that a carbon tax is the best way to reduce atmospheric carbon emissions. To get everyone on board, therefore, the economists suggest that all the money raised by the carbon tax should be returned to the residents of the United States. One possibility, for example, is to reduce income taxes by a dollar for every dollar raised by the carbon tax - tax burning not earning. Another possibility is to give each U.S. citizen an equal "carbon dividend." Here the economists' signatories are making a political point. A carbon-dividend might be a good way of selling the carbon tax to a large number of voters, especially as the dividend would be more than most voters would pay in tax.

Carbon Taxes Around the World

Coal powered the industrial revolution, and for more than 150 years coal was a major source of energy for the United Kingdom. On April 21, 2017, however, the United Kingdom went 24 hours without any electricity generated from coal-the first time this had happened since the 1880s. Coal use had been slowly declining in the United Kingdom since its peak in the 1950 but as late as 2012, coal still accounted for nearly 20% of UK. energy use. In 2013, however, the United Kingdom introduced a carbon tax and coal use began a rapid and dramatic decline. By 2017, coal accounted for only 5% of energy use. By 2025, it's expected that coal will be phased out entirely.

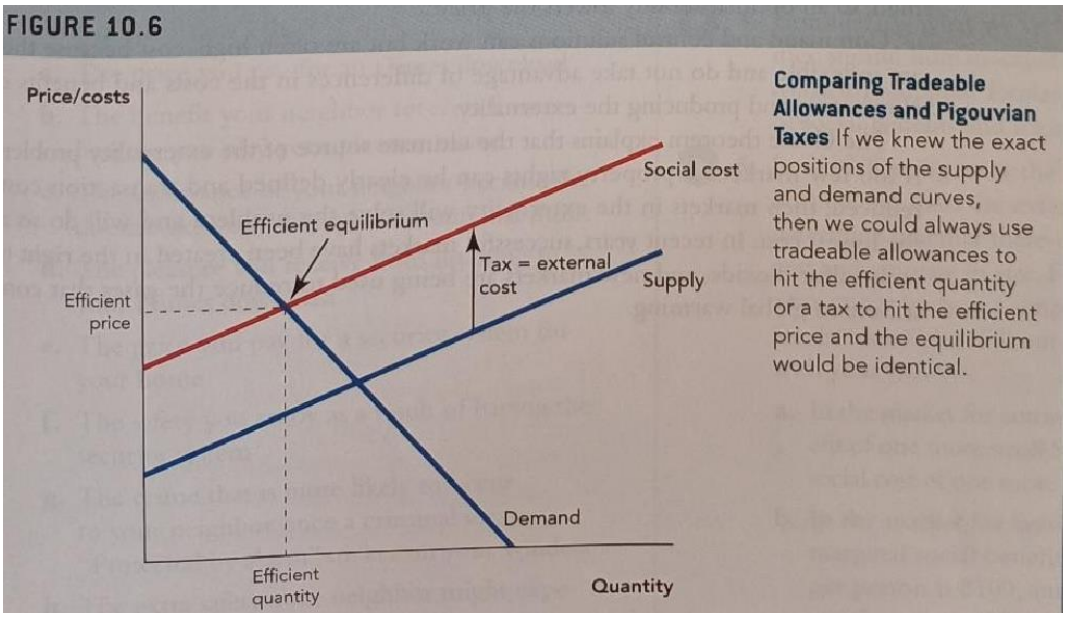
Phasing out coal will not only reduce carbon emissions- it will also increase health, as coal burning emissions are especially toxic. Indeed, some types of pollution are so toxic that they can reduce productivity, meaning that taxing them could result in net gains to production!

The United Kingdom's carbon tax raised the price of coal relative to other energy sources such as solar, wind, and natural gas. Natural gas is a carbon- emitting fuel, but it emits carbon at half the rate of coal for the same amount of energy, so switching to natural gas reduced the tax on electricity generators and the tax on the environment.

Other countries around the world have also introduced carbon taxes. Canada has a carbon tax and the revenues from the tax are rebated back to Canadian citizens. Mexico, Australia, and Norway also have carbon taxes, and China is planning to slowly introduce the largest tradeable allowance program for carbon (cap and trade) in the world beginning in 2020. Although there is no federal carbon tax in the United States, California has a tradeable allowance program, and there are several regional programs, including the Regional Greenhouse Gas Initiative that covers nine states in the Northeast.

Comparing a Carbon Tax With Tradable Allowances (Cap and Trade).

There is a close relationship between using carbon taxes and tradeable allowances to solve the externality problem. A tax set equal to the level of the external cost is equivalent to tradeable allowances, where the number of allowances is set equal to the efficient quantity. To achieve the efficient equilibrium in Figure 10.6, for example, the government can either use taxes to raise the price to the efficient price or it can use allowances to reduce the quantity to the efficient quantity. The equilibrium is identical no matter which method is used.



A major difference between taxes and tradeable allowances (cap and trade) is not economic but political. With a tax, firms must pay the government for each ton of pollutant that they emit. With tradeable allowances, firms must either use the allowances that they are given or, if they want to emit more, they must buy allowances from other firms. Either way, firms that are given allowances in the initial allocation get a big benefit compared with having to pay taxes. Thus, some people say that allowances equal corrective taxes plus corporate welfare.

That's not necessarily the best way of looking at the issue, however. First, allowances need not be given away; they could be auctioned to the highest bidder, as under some proposed tradeable allowance programs for carbon dioxide this would also raise significant tax revenue. Making progress against global warming, moreover, may require building a political coalition. A carbon tax pushes one very powerful and interested group, the large energy firms, into the opposition. If tradeable allowances are instead given to firms initially, there is a better chance of bringing the large energy firms into the coalition. Perhaps it's not fair that politically powerful groups must be bought off, but as Otto von Bismarck, Germany's first chancellor, once said, "Laws are like sausages, it is better not to see them being made." We can only add that producing both laws and sausages requires some pork.

III - International negotiations

[The CORE Econ Team, 2023, pp. 206, 208-212]

Modelling the global climate change problem

Why has it proved so difficult for international negotiations to make progress in limiting climate change? The success of the Montreal Protocol in protecting the ozone layer contrasts with the relative failure to reduce emissions responsible for global warming. The reasons are partly scientific. The alternative technologies to CFCs were well developed and the benefits relative to costs for large industrial countries, such as the US, were much clearer than in the case of greenhouse gas emissions.

Reducing carbon emissions requires much greater changes, across many industries and affecting all members of society. One of the obstacles at the United Nations' annual climate change negotiations has been disagreement over how to share the costs and benefits of limiting emissions between countries—and in recent years, the heavy costs some countries now face from the effects of past emissions elsewhere.

To explore the possible situations facing climate negotiators, we will model them as a game between two large countries, hypothetically labelled China and the US, each considered as if it were a single individual. First, we identify possible equilibria when each country behaves strategically; then we can think about how an agreed outcome might be achieved.

Figure 4.23a shows the outcomes of two alternative strategies: Restrict (taking measures to reduce emissions, for example by regulating or taxing the use of fossil fuels) and BAU (continuing with 'business as usual').

What we can expect to happen depends on the pay-offs in each outcome. The essential features of the problem can be captured using an ordinal scale from Best to Worst: it is the order of the pay-offs, not the size, that matters. Figure 4.23b shows two games, corresponding to different sets of hypothetical pay-offs.

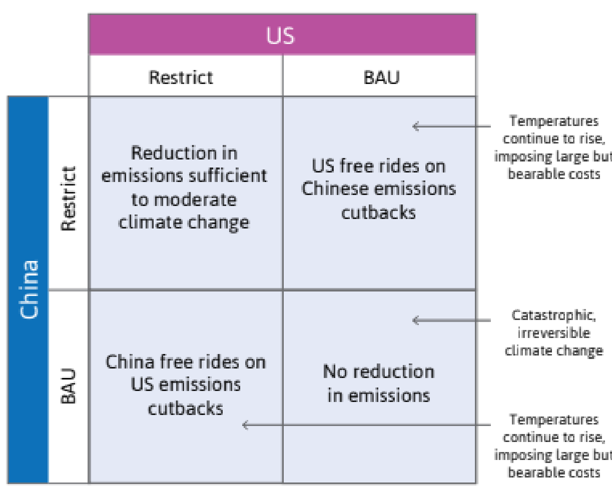


Figure 4.23a Outcomes of climate change policies.

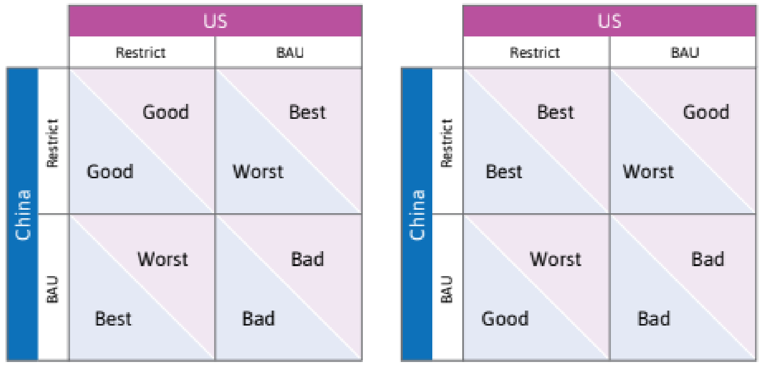


Figure 4.23b Two different climate policy games.

If you work out the best responses and find the Nash equilibria in each case, you will realise that the game on the left is a prisoners' dilemma, in which BAU is a dominant strategy for each country, leading to a Bad outcome for both. The game on the right is a coordination game, similar to the rice–cassava game in the box p.14 except that the players would like to coordinate on the same strategy, rather than the opposite one. There are two Nash equilibria: one is the Best outcome, in which both countries restrict emissions. But the Bad outcome in which neither do so is also an equilibrium, and if each country expects the other to choose BAU following their past behaviour, we can predict that they may be stuck in the (BAU, BAU) equilibrium.

Figure 4.23c presents a third model. It also shows the players' best responses, and hypothetical numerical pay-offs indicating the value of each possible outcome to the citizens of each country. The worst outcome for both countries is that both persist with BAU, thereby running a significant risk of human (and many other species') extinction. The best for each is to continue with BAU and let the other one Restrict. The only way to moderate climate change significantly is for both to Restrict.

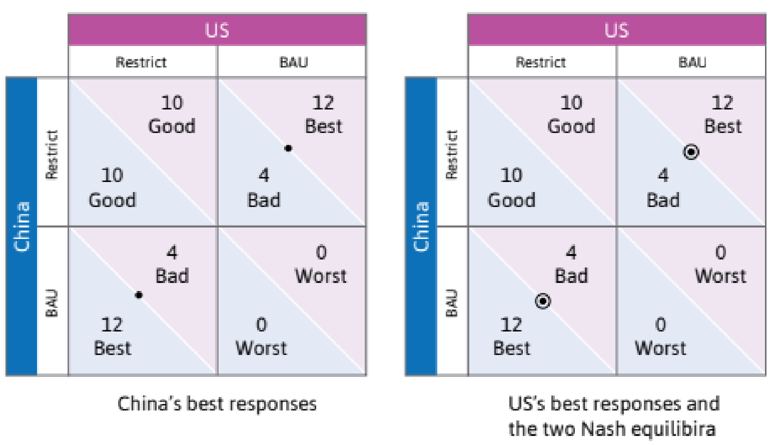


Figure 4.23c Best responses in a climate change game with a conflict of interest.

This is another coordination game with two equilibria, but now there is a conflict of interest between the players. This game is what is termed a **hawk–dove game**: players can act like an aggressive and selfish Hawk, or a peaceful and sharing Dove. In the climate change version, Doves Restrict and Hawks continue with BAU. The conflict of interest is that each country does better if it plays Hawk while the other plays Dove.

It captures a situation that is different from the previous two. Both countries have incentives to avoid catastrophic climate change. But they strongly prefer that the other should bear the costs of reducing emissions: each would like to wait to determine if the other will move first.

The Pareto-efficient allocation in which both countries restrict emissions also has the highest joint pay-offs. We can think of this as the best outcome for the world as a whole. But it is not an equilibrium.

Applying the hawk–dove game to climate policy

How do you think the hawk–dove game would be played in reality? Can the conflict of interest be resolved?

If one country could commit itself to BAU so that the other was certain that it would not consider any other strategy, then the other would play Restrict to avoid catastrophe. But this is true for both countries.

Negotiations are bound to be difficult, since each country would prefer the other to take the lead on restricting carbon emissions. The real climate negotiations are of course more complex—virtually all countries in the world are involved. Pay-offs may be different for these varied players. For example, in 2021 China produced 31% of the world's total carbon emissions, the US was second with 44% of China's level, followed by India. On a per-capita basis, China produced 55% of the emissions that the US did, and India produced 13% of US emissions.

Using public policy to change the game

How could the global social dilemma of climate change policy, as represented in this game, be solved? Could the governments of the world simply prohibit or severely limit emissions that contribute to the problem of climate change? This would amount to changing the game by altering available strategies by making BAU illegal. But who would enforce this law? There is no world government that could take a government that violated the law to court (and lock up its head of state!).

If the climate change social dilemma is to be addressed, Restrict must be in the interests of each of the parties. Consider the bottom-left corner (China plays BAU, US plays Restrict) equilibrium. If the pay-offs to China for playing Restrict were higher, when that is what the US is doing, then (Restrict, Restrict) might become an equilibrium. Indeed, in the eyes of many climate change scientists and concerned citizens, the aim of global environmental policy is to change the game so that (Restrict, Restrict) becomes a Nash equilibrium.

A number of mechanisms, aided by policy, could accomplish this:

- *Sustainable consumer lifestyles*: As a result of their concern for the wellbeing of future generations, people could come to prefer lifestyles that use fewer goods and services of the kind that result in environmental degradation. This would make the Restrict policy less costly and the BAU strategy less desirable.
- *Governments could stimulate innovation and the diffusion of cleaner technologies:* They might do this by, for example, raising the price of goods and services that result in carbon and other emissions, which would discourage their use. In the process, the use of cleaner technologies

would become cheaper, lowering the cost of Restrict. For example, renewable energy has become much cheaper. In some regions, it is now the cheapest energy option, which means Restrict is no longer more expensive than BAU. Self-interested behaviour will result in lower carbon emissions.

- *A change in norms:* Citizens, non-governmental organizations (NGOs), and governments can promote a norm of climate protection and sanction or shame countries that do nothing to limit climate change. This would also reduce the attractiveness of BAU.
- *Countries can share the costs of Restrict more evenly:* This is possible if, for example, a country for whom Restrict is prohibitively expensive instead helps another country where it is less expensive to Restrict. An example would be paying countries in the Amazon basin to conserve the rainforest.

Following the 2015 Paris Agreement (https://tinyco.re/8890909), almost all countries submitted individual plans for cutting emissions. Although there is no way that the agreement could be enforced, and these plans are not yet consistent with the goal of limiting the global temperature rise to 1.5°C, it is widely considered as a basis for further international cooperation. The Paris Agreement should:

- allow countries to better understand the costs of restricting emissions
- encourage economic players to innovate in order to further lower the costs
- strengthen norms that reduce the attractiveness of BAU
- establish a base of trust to share some of the costs of Restrict and negotiate more ambitiously in the future.

Anil's land is better for growing cassava, and Bala's for rice. But now if the two farmers produce the same crop, there is such a large fall in price that it is better for each to specialize, even in the crop they are less suited to grow. Follow the steps in Figure 4.21 to find the two equilibria.

Whatever their neighbour does, Anil and Bala each prefer to do the opposite. (Cassava, Rice) and (Rice, Cassava) are both Nash equilibria. This is a coordination game: each player would like to ensure that their action coordinates with their opponent's action.

Which equilibrium would we expect to observe in this game?

It is clear that the Nash equilibrium (Cassava, Rice), where they specialize in the crop they produce best, is preferred to the other Nash equilibrium, (Rice, Cassava), by both farmers.

Could we say, then, that we would expect Anil and Bala to engage in the best division of labour between the two crops? Not necessarily. Remember, we are assuming that they take their decisions independently, without communicating. Imagine that Bala's father had been especially good at growing cassava (unlike his son) and so the land remained dedicated to cassava even though it was better suited to rice. In response to this, Anil knows that Rice is his best response to Bala's Cassava: he decides to grow rice. Bala would have no incentive to switch to what he is good at: growing rice.

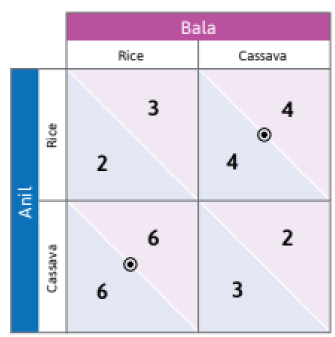


Figure 4.21 A third rice–cassava game: more than one Nash equilibrium.

1. Anil's best response to Rice
If Bala is going to choose Rice, Anil's best response is to choose Cassava. We place a dot in the bottom left-hand cell.

2. Anil's best response to Cassava
If Bala is going to choose Cassava, Anil's best response is to choose Rice. Place a dot in the top right-hand cell. Anil does not have a dominant strategy.

3. Bala's best responses
If Anil chooses Rice, Bala's best response is to choose Cassava, and if Anil chooses Cassava, Bala should choose Rice. The circles show Bala's best responses. He doesn't have a dominant strategy either.

4. There are two Nash equilibria
If Anil chooses Cassava and Bala chooses Rice, both of them are playing best responses (a dot and a circle coincide). So (Cassava, Rice) is a Nash equilibrium. But so is (Rice, Cassava).

The example makes an important point. If there is more than one Nash equilibrium, and if people choose their actions independently, then the players can get 'stuck' in an equilibrium in which all players are worse off than they would be at the other equilibrium. We would not call the game in Figure 4.21 an invisible hand game —the players may not reach the outcome that is best for both of them.

IV- Stock Externalities, Discounting and the Social Cost of Carbon.

[Pindyck & Rubinfeld, 2017, pp. 694-697]

Global warming is thought to result from the accumulation of carbon dioxide and other greenhouse gasses (GHGs) in the atmosphere. (As the GHG concentration grows, more sunlight is absorbed into the atmosphere rather than being reflected away, causing an increase in average temperatures.) GHG emissions do not cause the kind of immediate harm that sulfur dioxide emissions cause. Rather, it is the stock of accumulated GHGs in the atmosphere that ultimately causes harm. Furthermore, the dissipation rate for accumulated GHGs is very low: Once the GHG concentration in the atmosphere has increased substantially, it will remain high for many years, even if further GHG emissions were reduced to zero. That is why there is concern about reducing GHG emissions now rather than waiting for concentrations to build up (and temperatures to start rising) fifty or more years from now.

Stock externalities (like flow externalities) can also be positive. An example is the stock of "knowledge" that accumulates as a result of investments in R&D. Over time, R&D leads to new ideas, new products, more efficient production techniques, and other innovations that benefit society as a whole, and not just those who undertake the R&D. Because of this positive externality, there is a strong argument for the government to subsidize R&D. Keep in mind, however, that it is the stock of knowledge and innovations that benefits society, and not the flow of R&D that creates the stock.

The capital that a firm owns is measured as a stock, i.e., as a quantity of plant and equipment that the firm owns. The firm can increase its stock of capital by purchasing additional plant and equipment, i.e., by generating a flow of investment expenditures. (inputs of labor and raw materials are also measured as flows, as is the firm's output.) This distinction is important, because it helps the firm decide whether to invest in a new factory, equipment, or other capital. By comparing the *present discounted value* (PDV) of the additional profits likely to result from the investment to the cost of the investment, i.e., by calculating the investment's *net present value* (NPV), the firm can decide whether or not the investment is economically justified. The same net present value concept applies when we want to analyze how the government should respond to a stock externality—though with an additional complication. For the case of pollution, we must determine how any ongoing level of emissions leads to a buildup of the stock of pollutant, and we must then determine the economic damage likely to result from that higher stock. We will then be able to compare the present value of the ongoing costs of reducing emissions each year to the present value of the economic benefits resulting from a reduced future stock of the pollutant.

Stock Buildup and Its Impact

Let's focus on pollution to see how the stock of a pollutant changes over time. With ongoing emissions, the stock will accumulate, but some fraction of the stock, δ, will dissipate each year. Thus, assuming the stock starts at zero, in the first year, the stock of pollutant (S) will be just the amount of that year's emissions (E):

$$S_1 = E_1$$

In the second year, the stock of pollutant will equal the emissions that year plus the nondissipated stock from the first year—

$$S_2 = E_2 + (1 - \delta)S_1$$

—and so on. In general, the stock in any year t is given by the emissions generated that year plus the nondissipated stock from the previous year:

$$S_t = E_t + (1 - \delta)S_{(t-1)}$$

If emissions are at a constant annual rate E, then after N years, the stock of pollutant will be[15]:

$$S_N = E[1 + (1 - \delta) + (1 - \delta)^2 + \cdots + (1 - \delta)^{N-1}]$$

As N becomes infinitely large, the stock will approach the long-run equilibrium level E/ δ.

The impact of pollution results from the accumulating stock. Initially, when the stock is small, the economic impact is small; but the impact grows as the stock grows. With global warming, for example, higher temperatures result from higher concentrations of GHGs: thus the concern that if GHG emissions continue at current rates, the atmospheric stock of GHGs will eventually become large enough to cause substantial temperature increases—which, in turn, could have adverse effects on weather patterns, agriculture, and living conditions. Depending on the cost of reducing GHG emissions and the future benefits of averting these temperature increases, it may make sense for governments to adopt policies that would reduce emissions now, rather than waiting for the atmospheric stock of GHGs to become much larger.

Numerical Example

We can make this concept more concrete with a simple example. Suppose that, absent government intervention, 100 units of a pollutant will be emitted into the atmosphere every year for the next 100 years; the rate at which the stock dissipates, δ, is 2 percent per year, and the stock of pollutant is initially zero. Table 18.1 shows how the stock builds up over time. Note that after 100 years, the stock will reach a level of 4,337 units. (If this level of emissions continued forever, the stock will eventually approach E/δ = 100/.02 = 5,000 units.)

TABLE 18.1 BUILDUP IN THE STOCK OF POLLUTANT

YEAR	E	S_t	DAMAGE ($ BILLION)	COST OF E = 0 ($ BILLION)	NET BENEFIT ($ BILLION)
2010	100	100	0.100	1.5	−1.400
2011	100	198	0.198	1.5	−1.302
2012	100	296	0.296	1.5	−1.204
...	...	...	...	...	...
2110	100	4,337	4.337	1.5	2.837
...	...	...	...	...	...
∞	100	5,000	5.000	1.5	3.500

Suppose that the stock of pollutant creates economic damage (in terms of health costs, reduced productivity, etc.) equal to $1 million per unit. Thus, if the total stock of pollutant were, say, 1000

[15] To see this, note that after 1 year, the stock of pollutant is $S_1 = E$, in the second year the stock is $S_2 = E + (1 - \delta)S_1 = E + (1 - \delta)E$, in the third year, the stock $S_3 = E + (1 - \delta)S_2 = E + (1 - \delta)E + (1 - \delta)^2E$, and so on. As N becomes infinitely large, the stock approaches E/δ.

units, the resulting economic damage for that year would be $1 billion. And suppose that the annual cost of reducing emissions is $15 million per unit of reduction. Thus, to reduce emissions from 100 units per year to zero would cost 100 × $15 million = $1.5 billion per year. Would it make sense, in this case, to reduce emissions to zero starting immediately?

To answer this question, we must compare the present value of the annual cost of $1.5 billion with the present value of the annual benefit resulting from a reduced stock of pollutant. Of course, if emissions were reduced to zero starting immediately, the stock of pollutant would likewise be equal to zero over the entire 100 years. Thus, the benefit of the policy would be the savings of social cost associated with a growing stock of pollutant. Table 18.1 shows the annual cost of reducing emissions from 100 units to zero, the annual benefit from averting damage, and the annual net benefit (the annual benefit net of the cost of eliminating emissions). As you would expect, the annual net benefit is negative in the early years because the stock of pollutant is low; the net benefit becomes positive only later, after the stock of pollutant has grown. To determine whether a policy of zero emissions makes sense, we must calculate the NPV of the policy, which in this case is the present discounted value of the annual net benefits shown in Table 18.1. Denoting the discount rate by R, the NPV is:

$$NPV = (-1.5 + .1) + \frac{(-1.5 + .198)}{1 + R} + \frac{(-1.5 + .296)}{(1 + R)^2} + \cdots + \frac{(-1{,}5 + 4{,}337)}{(1 + R)^{99}}$$

Is this NPV positive or negative? The answer depends on the discount rate, R. Table 18.2 shows the NPV as a function of the discount rate. (The middle row of Table 18.2, in which the dissipation rate δ is 2 percent, corresponds to Table 18.1. Table 18.2 also shows NPVs for dissipation rates of 1 percent and 4 percent.) For discount rates of 4 percent or less, the NPV is clearly positive, but if the discount rate is large, the NPV will be negative.

TABLE 18.2 NPV OF "ZERO EMISSIONS" POLICY

		DISCOUNT RATE, *R*				
		.01	.02	.04	.06	.08
DISSIPATION RATE, δ	.01	108.81	54.07	12.20	−0.03	−4.08
	.02	65.93	31.20	4.49	−3.25	−5.69
	.04	15.48	3.26	−5.70	−7.82	−8.11

Note: Entries in table are NPVs in $billions. Entries for δ = .02 correspond to net benefit numbers in Table 18.1.

Table 18.2 also shows how the NPV of a "zero emissions" policy depends on the dissipation rate, δ. If δ is lower, the accumulated stock of pollutant will reach higher levels and cause more economic damage, so the future benefits of reducing emissions will be greater. Note from Table 18.2 that for any given discount rate, the NPV of eliminating emissions is much larger if δ = .01 and much smaller if δ = .04. As we will see, one of the reasons why there is so much concern over global warming is the fact that the stock of GHGs dissipates very slowly; δ is only about .005.

Formulating environmental policy in the presence of stock externalities therefore introduces an additional complicating factor: What discount rate should be used? Because the costs and benefits of a policy apply to society as a whole, the discount rate should likewise reflect the opportunity cost to society of receiving an economic benefit in the future rather than today. This opportunity cost, which should be used to calculate NPVs for government projects, is called the social rate of discount. But there is little agreement among economists as to the appropriate number to use for the social rate of discount.

In principle, the social rate of discount depends on three factors: (1) the expected rate of real economic growth; (2) the extent of risk aversion for society as a whole; and (3) the "rate of pure time preference" for society as a whole. With rapid economic growth, future generations will have higher incomes than current generations, and if their marginal utility of income is decreasing (i.e., they are risk-averse), their utility from an extra dollar of income will be lower than the utility to someone living today; that's why future benefits provide less utility and should thus be discounted. In addition, even if we expected no economic growth, people may simply prefer to receive a benefit today than in the future (the rate of pure time preference). Depending on one's beliefs about future real economic growth, the extent of risk aversion for society as a whole, and the rate of pure time preference, one could conclude that the social rate of discount should be as high as 6 percent—or as low as 1 percent. And herein lies the difficulty. With a discount rate of 6 percent, it is hard to justify almost any government policy that imposes costs today but yields benefits only 50 or 100 years in the future (e.g., a policy to deal with global warming). Not so, however, if the discount rate is only 1 or 2 percent.[16] Thus for problems involving long time horizons, the policy debate often boils down to a debate over the correct discount rate.

[The CORE Econ Team, 2023, pp. 460-462]

Application: Discounting, external effects, and the future of the planet.

Discount rates are central to the discussion in economics of how best to address climate change and other environmental damages. But what is discounted is not the value placed by a citizen on their consumption later (as opposed to consumption now) but instead the value we place on the consumption of people living in the future compared to our own generation.

Our economic activity today will affect how climate changes in the distant future, so we are creating consequences that others will bear. This is an extreme form of external effects that we study throughout the book. It is extreme not only in its potential consequences, but also in that those who will suffer the consequences are future generations. But the future generations that will bear the consequences of our decisions are unrepresented in the policymaking process today. The only way the wellbeing of these unrepresented generations will be taken into account at the environmental bargaining tables is the fact that most people care about, and would like to behave ethically toward, others.

These social preferences underlie the debates among economists about how much we should value the future benefits and costs of the climate change decisions that we make today. In the model developed in this unit, we know that the actor (say, Julia) is best off when she chooses the combination of consumption now and later where the MRS = MRT; that is, where her subjective discount rate is equal to the rate of interest.

In considering alternative environmental policies addressed to climate change, how much we value the wellbeing of future generations is commonly measured by an interest rate; that is, by applying the same MRS = MRT approach. This raises the question of what interest rate should be used to discount

[16] For example, with a discount rate of 6 percent, $100 received 100 years from now is worth only $0.29 today. With a discount rate of 1 percent, that same $100 is worth $36.97 today, i.e., 127 times as much.

future generations' costs or benefits. Economists disagree about how this discounting process should be done.

When economists disagree: The discounting dilemma: How should we account for future costs and benefits?

When considering policies, economists seek to compare the benefits and costs of alternative approaches, often in cases where some people bear the costs and others enjoy the benefits. Doing this presents especially great challenges when the policy problem is climate change. The reason is that costs will be borne by the present generation, but most of the benefits of a successful policy to limit CO2 emissions, for example, will be enjoyed by people in the future, many of whom are not yet alive.

Put yourself in the shoes of an impartial policymaker and ask yourself: Are there any reasons why, in summing up the benefits and costs of such a policy, I should value the benefits expected to be received by future generations any less than the benefits and costs that will be borne by people today? Two reasons come to mind:

- *Technological progress and diminishing marginal utility:* People in the future may have lesser unmet needs than we do today. For example, as a result of continuing improvements in technology, they may be richer (either in goods or free time) than we are today, so it might seem fair that we should not value the benefits they will receive from our policies as highly as we value the costs that we will bear as a result.
- *Extinction of the human species:* There is a small possibility that future generations will not exist because humanity becomes extinct.

These are good reasons why we might discount the benefits received by future generations. Neither of these reasons for discounting is related to intrinsic impatience.

This was the approach adopted in the 2006 Stern Review on the Economics of Climate Change. (read the executive summary on the UK National Archives website (https://tinyco.re/6397444)). Nicholas Stern, an economist, selected a discount rate to take account of the likelihood that people in the future would be richer. Based on an estimate of future productivity increases, Stern discounted the benefits to future generations by 1.3% per annum. To this he added a 0.1% per annum discount rate to account for the risk that in any future year there might no longer be surviving generations. Based on this assessment, Stern advocated an urgent and fundamental shift in the policies of governments and businesses to ensure substantial investments to limit CO_2 emissions today in order to protect the environment of the future.

Several economists, including William Nordhaus, criticized the Stern Review for its low discount rate (https://tinyco.re/9892599). Nordhaus wrote that Stern's choice of discount rate 'magnifies impacts in the distant future'. He concluded that, with a higher discount rate, 'the Review's dramatic results [Stern's policy conclusions above] disappear'.

Nordhaus advocated the use of a discount rate of 4.3%, which gave vastly different implications. Discounting at this rate means that a $100 benefit occurring 100 years from now is worth only $1.48 today, while under Stern's 1.4% rate it would be worth $24.90. This means, a policymaker using Nordhaus's discount rate would approve of a project that would save future generations $100 in environmental damages only if it cost less than $1.48 today. A policymaker using Stern's 1.4% would approve the project only if it cost less than $24.90.

Not surprisingly, then, Nordhaus's recommendations for climate change abatement were far less extensive and less costly than those that Stern proposed. For example, Nordhaus proposed a carbon price of $35 per ton in 2015 to deter the use of fossil fuels, whereas Stern recommended a price of $360.

Why did the two economists differ so much? They agreed on the need to discount for the likelihood that future generations would be better off. But Nordhaus had an additional reason to discount future benefits: intrinsic impatience.

Reasoning as we did in Julia's choice of consumption now or later, Nordhaus used estimates based on market interest rates (the slope of the feasible set) as measures of how people today value their own future versus present consumption. Using this method, he came up with a discount rate of 3% to measure the way people discount future benefits and costs that they themselves may experience. Nordhaus included this in his discount rate, which is why Nordhaus's discount rate (4.3%) is so much higher than Stern's (1.4%).

Critics of Nordhaus pointed out that a psychological fact like our own impatience—how much more we value *our own* consumption now versus later—is not a reason to discount the needs and aspirations of *other people* in future generations. Stern's approach counts all generations as equally worthy of our concern for their wellbeing. Nordhaus, in contrast, takes the current generation's point of view and counts future generations as less worthy of our concern than the current generation, much in the way that, for reasons of intrinsic impatience, we typically value current consumption more highly than our own future consumption.

Is the debate resolved? The discounting question ultimately requires adjudicating between the competing claims of different individuals at different points in time. This involves questions of ethics on which economists will continue to disagree.

[Goolsbee, Levitt, & Syverson, 2019, p. 606]

One of the most important economic numbers in policy debates about climate change is the social cost of carbon (SCC). The SCC is the negative externality that will result from one additional unit of carbon dioxide emissions through its effects on climate change. Another way to describe the SCC is that it is how big the Pigouvian tax would have to be to lead to the socially optimal amount of carbon dioxide emissions.

Many environmental economists have tried to measure the social cost of carbon. It isn't easy, there is a lot of uncertainty about how the climate works, the types and magnitudes of economic effects that climate change will have, and how much people today should weigh the welfare of future generations. All these factors need to be taken into account to arrive at an estimate. That's why the estimates have varied widely, from less than $20 per metric ton to over $600 per metric ton.

A recent estimate by the Nobel Prize-winning economist William Nordhaus has received a lot of attention[17]. Using the latest version of a large model of the climate and the economy, he computes a SCC of about $36 per metric ton (in 2018 dollars). To put that in perspective, a typical car produces

[17] William D. Nordhaus, "Revisiting the Social Cost of Carbon," Proceedings of the National Academy of Sciences 114, no. 7 (2017): 1518–1523.

about 5 metric tons of carbon dioxide per year. Therefore, if Nordhaus's calculation was used to establish a climate change Pigouvian tax, it would be about $180 per year for a typical car.

You might be thinking, "Well, it's not as if $180 a year is nothing, but I would still keep driving if this was the tax. How is that going to stop my carbon emissions?" The answer is that it won't stop your carbon emissions, nor should it. You derive a benefit from being able to drive around; that's why you would pay the tax. Without a carbon tax, you would add to the climate change problem without paying for the damage you are doing. If a tax is imposed (and it is set at the true social cost of carbon dioxide emissions), you would pay for exactly the amount of damage you do. You will balance this cost against the benefit you obtain from your car and drive the optimal amount from a social perspective. This will be less than the amount you drove when there was no tax and you did not pay for your negative externality, but it will be more than nothing.

Notes to the figures

Fig 1.1

Stephen Broadberry. 2021. 'Accounting for the great divergence: recent findings from historical national accounting'.; Total Economy Database (https://tinyco.re/1587851).; S. N. Broadberry, B. Campbell, A. Klein, M. Overton, and B. van Leeuwen, B. 2015. British Economic Growth, 1270–1870 (https://tinyco.re/6743321). Cambridge: Cambridge University Press.; S. Broadberry, H. Guan, and D. Li. 2018. 'China, Europe and the Great Divergence: A Study in Historical National Accounting' (https://tinyco.re/9902110) Journal of Economic History 78: pp. 955–1000.; J. P. Bassino, S. Broadberry, K. Fukao, B. Gupta, and M. Takashima, M. 2019. 'Japan and the Great Divergence, 730–1874' Explorations in Economic History 72: pp. 1–22.; S. Broadberry, J. Custodis, and B. Gupta, B. 2015. 'India and the Great Divergence: An Anglo-Indian Comparison of GDP per Capita, 1600–1871' (https://tinyco.re/ 3221560) Explorations in Economic History 55: pp. 58–75.; P. Malanima. 2011. 'The Long Decline of a Leading Economy: GDP in Central and Northern Italy, 1300–1913'. European Review of Economic History 15: pp. 169–219.; S. Broadberry and L. Gardner. 2022. 'Economic Growth in Sub-Saharan Africa, 1885–2008: Evidence From Eight Countries' (https://tinyco.re/8802100). Explorations in Economic History 83: 101424. Note: The historical data is being improved continuously and the best data is provided in Figure 1.1 for the six countries shown. An alternative source of data is available for many more countries in the interactive chart.

Fig 1.2a

Pierre Friedlingstein, Matthew W. Jones, Michael O'Sullivan, et al. 2019. 'Global Carbon Budget 2019' (https://tinyco.re/2898770). Earth System Science Data 11: pp. 1783– 1838. doi: 10.5194/ essd-11-1783-2019.; Pieter Tans NOAA/GML and Ralph Keeling, Scripps Institution of Oceanography. 2022. 'Trends in Atmospheric Carbon Dioxide' (https://tinyco.re/4421890).; D. Gilfillan, G. Marland, T. Boden, and R. Andres, R. 2021. 'Global, Regional, and National Fossil Fuel CO2 Emissions' (https://tinyco.re/ 3338780). Carbon Dioxide Information Analysis Center (CDIAC) Datasets. Accessed: September, 2021.

Fig 1.2b

See more https://tinyco.re/8926412. Michael E. Mann, Zhihua Zhang, Malcolm K. Hughes, Raymond S. Bradley, Sonya K. Miller, Scott Rutherford, and Fenbiao Ni. 2008. 'Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia' (https://tinyco.re/ 1009800). Proceedings of the National Academy of Sciences 105 (36): pp. 13252–13257.; C. P. Morice, J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2012. 'Quantifying uncertain- ties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset' (https://tinyco.re/6765840), Journal of Geophysical Research 117. D08101, doi:10.1029/2011JD017187.

Fig 2.20

Pieter Tans, NOAA/GML, and Ralph Keeling, Scripps Institution of Oceanography. 2022. Trends in Atmospheric Carbon Dioxide (https://tinyco.re/8976788); D. Gilfillan, G. Marland, T. Boden, and R. Andres, R. 2021. Global, Regional, and National Fossil-Fuel CO_2 Emissions (https://tinyco.re/4356621). Carbon Dioxide Information Analysis Center (CDIAC) Datasets. Accessed: September 2021.; Michael E. Mann, Zhihua Zhang, Malcolm K. Hughes, Raymond S. Bradley, Sonya K. Miller, Scott Rutherford, and Fenbiao Ni. 2008. 'Proxy-based reconstructions of hemispheric and global surface temperature variations over the past two millennia' (https://tinyco.re/ 1009800). Proceedings of the National Academy of Sciences 105 (36): pp. 13252–13257.; C. P. Morice, , J. J. Kennedy, N. A. Rayner, and P. D. Jones. 2012. Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 dataset (https://tinyco.re/6765840). Journal of Geophysical Research 117. D08101, doi:10.1029/2011JD017187. Note: This data is the same as in Figures 1.2a and 1.2b. Temperature is average northern hemisphere temperature.

Fig 2.21

The World Bank. 2021. 'World Development indicators (https://tinyco.re/ 1998076)'.; EPI. 2018. 'Environmental Protection Index 2018 (https://tinyco.re/5473228)'. Yale Center for Environmental Law and Policy (YCELP) and the Center for International Earth Science Information Network. Note: Three small very high-income countries (Kuwait, Luxembourg, and Qatar) are not shown.

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Our World in Data (https://tinyco.re/2209091). Lazard's Levelized Cost of Energy Analysis (https://tinyco.re/7666512). Version 13. 2019.